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Original Article

Numerical Investigation of Passive Vibration Damping Using Butyl-Viscoelastic and Particle-Viscoelastic Damping Materials

Anand Rengaraj[1], Arohan Sharma[1], Gaurav Sharma[1], A. Kumaraswamy[1*]

[1]*Department of Mechanical Engineering, Defence Institute of Advanced Technology, Pune, India.*

**Corresponding Author : adepukumarswamy1968@gmail.com*

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Abstract *- This study investigates the damping performance of Viscoelastic Damping Materials (VDM) and Particle-Enhanced VDM (P-VDM) in various configurations, including Free Layer Damping (FLD), Constrained Layer Damping (CLD), and multilayer CLD structures. Modal and harmonic response analyses were conducted on a steel beam with and without damping treatments to evaluate vibrational performance. The results show that incorporating P-VDM significantly improves damping efficiency, reducing deformation and vibrational amplitudes more effectively than traditional VDM. A five-layer CLD structure using P-VDM exhibited the best results, with maximum deformation reduced to 0.45 mm and resonance frequencies shifted to 730 Hz. Harmonic response analysis revealed a reduction in peak amplitude to 1580 mm/N with stabilization at 400 mm/N, demonstrating exceptional energy dissipation. These findings highlight the potential of P-VDM in advanced vibration control applications, particularly in multilayer configurations.*

Keywords *- Vibration damping, CLD, FLD, Viscoelastic material, Modal analysis, Harmonic analysis, Butyl rubber.*

1. Introduction

The phenomenon of vibration has been inherently linked to the development of machinery and mechanical systems since their inception. Any moving or contacting part generates vibrations characterized by specific frequencies, wavelengths, and amplitudes. While vibrations are often perceived as detrimental, they also serve as valuable indicators of a machinery's health, enabling Condition-Based Predictive Maintenance (CBPM) without requiring disassembly [1-3]. Noise and vibration studies became integral to CBPM methodologies in the marine industry post-World War II when untimely machinery failures in warships were traced to inadequate maintenance practices. Consequently, noise and vibration analyses were incorporated into maintenance protocols to enhance reliability and operational readiness [4-6].

Resonance, a particularly destructive phenomenon, becomes critical in enclosed spaces with multiple machines operating in close proximity, such as a marine environment. The natural frequency of one machine may coincide with the resonant frequency of another component, leading to excessive vibrations, misalignment, accelerated wear, and eventual failure [2, 6]. In warships, where machinery must support vital operations such as propulsion, maneuvering, and combat readiness, uncontrolled vibrations can compromise structural integrity and functionality. Additionally, external factors such as collisions, wave-induced motions (e.g., surging, hogging, pitching, and rolling), and impacts on the ship's hull further amplify vibrations, transmitting them to bulkheads and onboard machinery [3-5].

Mitigating vibrations to the lowest possible level is thus a critical research focus. Vibration control can be achieved through damping, isolation, and shielding, using either active or passive measures. This study emphasizes passive vibration control techniques, particularly employing Viscoelastic Damping Materials (VDMs) in constrained layer configurations [7, 8].

Viscoelastic materials, owing to their dual elastic-viscous properties, are ideal for damping applications. These polymers exhibit chain-like molecular structures, with each chain storing thermal energy that facilitates internal motion. Damping in such materials is most effective during the "transitional phase," where stiffness variations are pronounced with temperature changes. The effectiveness of VDMs is governed by their mechanical properties, including shear modulus (G), Young's modulus (E), and loss factor (η), which determine their energy dissipation capabilities [9-11].

This study investigates the minimization of vibrations using Butyl and Particle-based VDMs, comparing their amplitude and damping performance in accordance with ASTM standards. Various configurations, including single and multi-layered Constrained Layer Damping (CLD) treatments, are analyzed for their effectiveness.

Furthermore, advancements in VDM technologies have introduced specialized materials tailored for specific applications. These include Particle VDMs (P-VDMs), Piezoelectric VDMs (PZ-VDMs), Butyl Rubber VDMs (BR-VDMs), Water-Based Coating VDMs (WC-VDMs), and Bitumen-based VDMs (B-VDMs). Each material demonstrates unique properties, operational temperature ranges, and application domains, from automotive and aerospace to marine environments [12-16].

For example, B-VDMs, composed of bitumen, synthetic rubber, and mineral fillers, are widely used in civil and military applications due to their cost-effectiveness, high damping ratio, and ease of implementation. Conversely, WC-VDMs, employing liquid dispersions for energy dissipation, offer fire resistance, environmental friendliness, and excellent adhesion properties, albeit at a higher cost. BR-VDMs, known for their superior mechanical energy absorption and customizable properties, find extensive use in the transportation industry for Noise, Vibration, and Harshness (NVH) reduction [17-21].

This paper explores the application of VDMs in both free-layer and constrained-layer configurations. Free-layer damping relies on cyclic tension and compression of the damping material bonded to a structure's surface, while constrained-layer damping employs an elastic outer layer that enhances energy dissipation through the shear deformation of the VDM. The results aim to provide insights into optimizing damping performance for advanced vibration control applications.

2. Methodology

This study employed ASTM standards to evaluate the vibration-damping properties of materials, including Young's modulus (E), loss factor (H), and shear modulus (G), across a frequency range of 50 to 5000 Hz and relevant temperature ranges. These properties are critical for materials used in applications such as building acoustics, structural vibration control, and noise mitigation. The materials tested included metals, rubbers, ceramics, reinforced epoxy matrices, plastics, and wood, typically configured as cantilever beam specimens for analysis.

The methodology adheres to several key assumptions to ensure consistency and accuracy. It is assumed that the plane sections of the specimen maintain uniform geometry; therefore, the viscoelastic layer's thickness must not exceed four times that of the base metal. The materials are expected to exhibit linear viscoelastic behavior, and measurements must remain within the linear range to produce valid results. For uniform beams, the peak displacement from the rest position should not exceed the thickness of the base beam. Furthermore, the force amplitude applied to the excitation transducer must remain constant across frequencies. If this condition is not met, the beam's response must be normalized by dividing it by the force amplitude. Lastly, the shear property equations exclude extensional terms for the damping layer, which is acceptable when the damping layer's modulus is significantly lower (by approximately ten times) than that of the base metal.

The cantilever beam study was conducted using SolidWorks simulation tools. The specifications for the modal and harmonic analysis are as follows:

- Mass of steel beam: 0.058784 kg
- Volume: 7.441×10^{-6} m³
- Density: 7,900 kg/m³
- Weight: 0.576083 N
- Material: AISI 1020 Steel
- Yield Strength: 3.51571×10^{8}N/m²
- Tensile Strength: 4.20507×10^{8}N/m²
- Elastic Modulus: 2.0×10^{11}N/m²
- Poisson's Ratio: 0.29
- Mesh Details:
    - Total Nodes: 3,262
    - Total Elements: 1,875
    - Element Size: 3.17372 mm
    - Maximum Aspect Ratio: 2.8992
    - Tolerance: 0.158686 mm

Steel beam of $(100\times15\times5)mm,$ as shown in Figure 1, is used in cantilever condition were analyzed. Models were subjected to controlled excitation conditions to analyze vibration amplitudes, damping ratios, and material responses under harmonic loading. This methodology, combining adherence to ASTM standards and detailed simulations, ensures reliable results for applications in noise and vibration control.

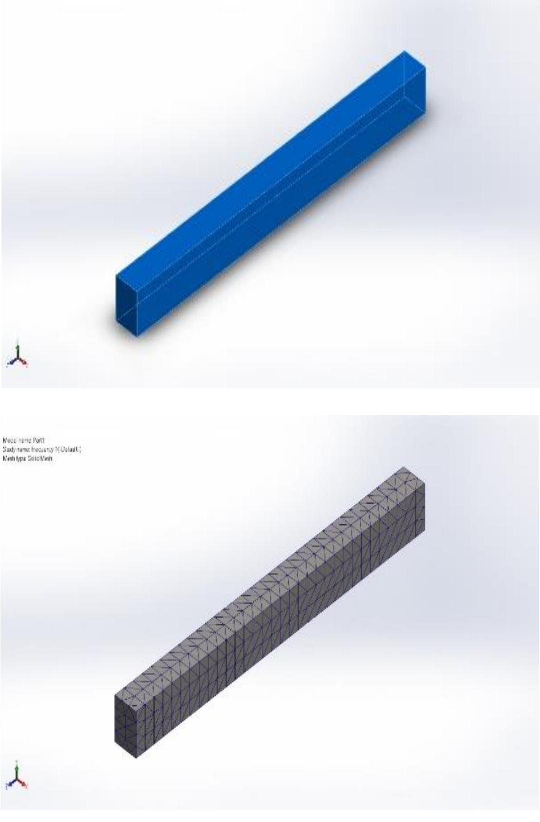


Fig. 1 steel beam of specified dimension and meshed cantilever beam

Figure 2 shows the arrangement of the particle viscoelastic damping material layer (P-VDM), which is used in this study for both CLD and multilayer CLD structures.

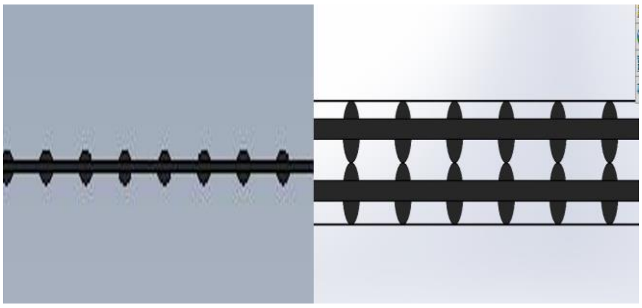


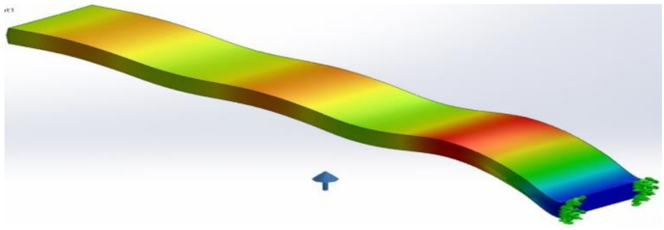
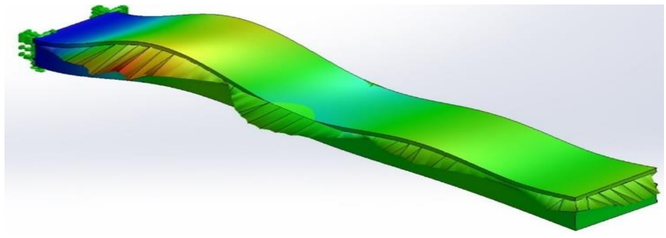
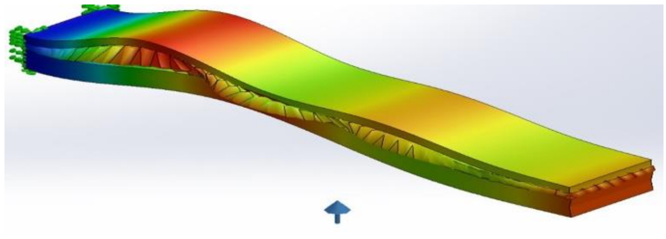
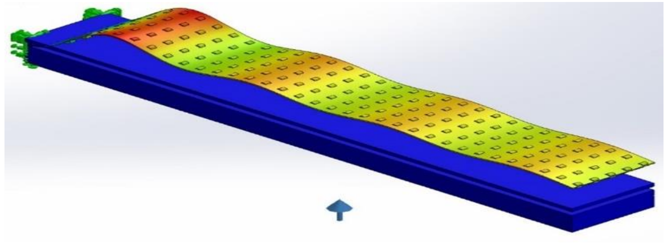
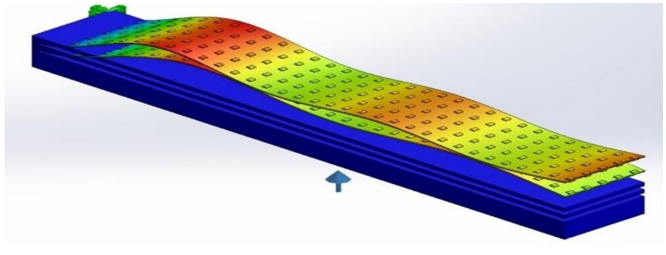
Fig. 2 P-VDM arrangement

3. Results and Discussion

3.1. Modal Analysis Result

The modal analysis results, summarized in Table 1, compare the Performance of various configurations, including an untreated steel beam, Free Layer Damping (FLD), Constrained Layer Damping (CLD), and multilayer CLD with Viscoelastic Damping Material (VDM) and Particle-VDM (P-VDM) layers. The untreated steel beam (Model 1) exhibited a maximum deformation of 1.24 mm at a natural frequency of 3800 Hz, reflecting its inability to dissipate vibrational energy. In contrast, Model 2, incorporating a 2 mm VDM layer over the steel beam, demonstrated a reduction in deformation to 0.89 mm at a natural frequency of 1850 Hz, showing moderate damping due to the viscoelastic properties of the material.

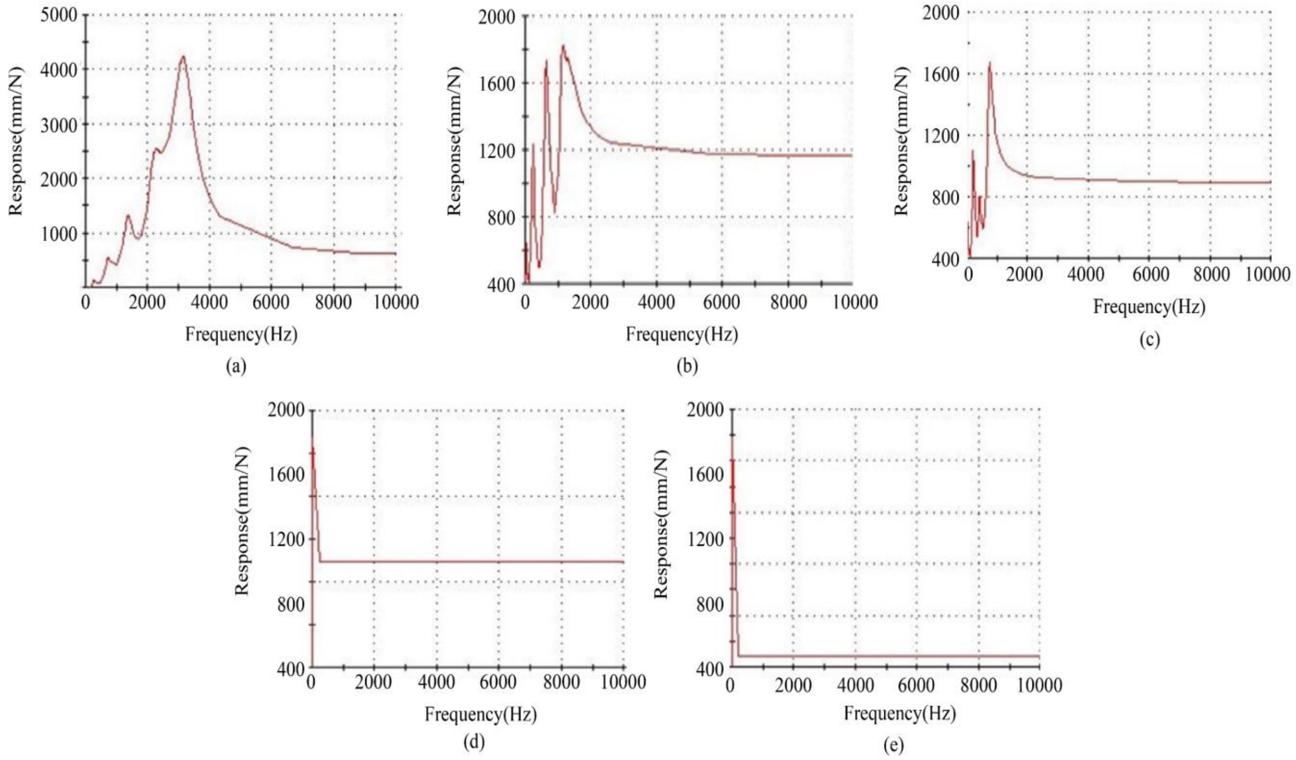
Table. 1 Modal analysis results

Model	Mode shape
Model -1 Mild steel Beam	
Model -2 FLD - VDM layer	
Model -3 CLD -VDM layer	
Model -4 CLD – P-VDM layer	
Model -5 Multilayer CLD- P-VDM layer	

Model 3, a CLD structure comprising a 2 mm VDM layer and a 2 mm constraining layer, further reduced the maximum deformation to 0.65 mm at 1750 Hz. This improvement can be attributed to the shear deformation in the VDM layer, which enhances energy dissipation. Replacing the VDM layer with P-VDM in Model 4 led to even better performance, with deformation decreasing to 0.54 mm at a lower natural frequency of 850 Hz. The enhanced damping efficiency of P-VDM highlights its superior energy dissipation properties. The best results were observed in Model 5, a multilayer CLD structure with two P-VDM layers and two constraining layers, each 2 mm thick. This configuration achieved a maximum deformation of just 0.45 mm at a natural frequency of 730 Hz, demonstrating the significant benefits of a multilayer approach in damping vibrational energy.

3.2. Harmonic Response Analysis

The harmonic response analysis provides further insights into the frequency-dependent damping performance of the models. The untreated steel beam (Model 1) exhibited a maximum response amplitude of 4200 mm/N at 3800 Hz, as shown in Figure 3(a), with no significant damping observed across the frequency spectrum. Adding a 2 mm VDM layer in the FLD structure (Model 2) resulted in a noticeable reduction, with a peak amplitude of 1810 mm/N at 1850 Hz, followed by stabilization at approximately 1200 mm/N.



(a)
(b)
(c)
(d)
(e)

Fig. 3 Frequency response function as displacement(mm/N) for all 5 models

In the CLD configuration with a VDM layer (Model 3), the response improved further. The maximum amplitude decreased to 1620 mm/N at 1750 Hz, with stabilization at around 900 mm/N, indicating better damping due to the combined action of the VDM and constraining layers. Replacing the VDM layer with P-VDM in Model 4 led to a significant improvement, with the peak amplitude reduced to 1600 mm/N at 850 Hz and subsequent stabilization at 1120 mm/N.

This result underscores the effectiveness of P-VDM as a damping material in CLD structures. The most substantial improvement was observed in the multilayer CLD structure with P-VDM layers (Model 5). The response amplitude was significantly reduced, with a peak amplitude of 1580 mm/N at 730 Hz, stabilizing at an exceptionally low value of 400 mm/N. This remarkable damping performance is attributed to the multilayer configuration, which allows for greater energy dissipation through enhanced shear deformation across multiple damping layers. The results of both the modal and harmonic analyses clearly demonstrate the superior damping performance of P-VDM compared to traditional VDM, especially when implemented in multilayer CLD configurations.

The shift in natural frequencies to lower values and the significant reduction in deformation and response amplitudes highlight the influence of damping material selection and configuration on dynamic performance. The multilayer CLD structure with P-VDM not only reduces vibrational amplitudes but also dissipates energy more effectively, making it an ideal choice for advanced vibration control applications. These findings validate the potential of P-VDM for use in noise and vibration mitigation in structures requiring high damping efficiency.

4. Conclusion

The study conclusively demonstrates the efficacy of Viscoelastic Damping Materials (VDMs) in enhancing vibration control and minimizing structural deformation. Through detailed numerical analysis, it was observed that the introduction of damping treatments, particularly Particle-based VDM (P-VDM), significantly mitigates vibration-induced displacement and stress development. The comparative analysis of different configurations highlights that multilayer CLD structures with P-VDM outperform traditional VDMs and single-layer setups, offering superior energy dissipation and resonance attenuation. Key insights reveal that while FLD structures provide basic damping, CLD configurations achieve markedly better results due to the additional shear deformation and energy dissipation. Furthermore, Particle-based VDMs exhibit enhanced damping efficiency, particularly in multilayer configurations, where their ability to reduce harmonic response amplitudes and control resonance effects is most evident. This underlines the critical importance of material selection and layer configuration in optimizing vibration control strategies.The findings not only validate the role of P-VDM as a robust damping material but also emphasize its potential for advanced industrial applications. Future research could focus on exploring hybrid configurations, further optimization of material properties, and experimental validation under real-world operating conditions. By advancing the understanding of viscoelastic damping mechanisms, this study contributes to the development of more effective solutions for vibration and noise control in engineering systems.

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